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DO6: Technologies for Lunar Surface Operation

Title: **NASA In-Situ Resource Utilization (ISRU) Technology and Development Project Overview**

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ABSTRACT

Since the Vision for Space Exploration (VSE) was released in 2004, NASA, in conjunction with international space agencies, industry, and academia, has continued to define and refine plans for *sustained* and *affordable* robotic and human exploration of the Moon and beyond. With the goal of establishing a lunar Outpost on the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth's economic sphere, a change in how space exploration is performed is required. One area that opens up the possibility for the first time of breaking our reliance on Earth supplied consumables and learn to "live off the land" is In-Situ Resource Utilization (ISRU). ISRU, which involves the extraction and processing of space resources into useful products, can have a substantial impact on mission and architecture concepts. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. However, ISRU is an unproven capability for human lunar exploration and can not be put in the critical path of lunar Outpost success until it has been proven. Therefore, ISRU development and deployment needs to take incremental steps toward the desired end state. To ensure ISRU capabilities are available for pre-Outpost and Outpost deployment by 2020, and mission and architecture planners are confident that ISRU can meet initial and long term mission requirements, the ISRU Project is developing technologies and systems in three critical areas: (1) Regolith Excavation, Handling and Material Transportation; (2) Oxygen Extraction from Regolith; and (3) Volatile Extraction and Resource Prospecting, and in four development stages: (I) Demonstrate feasibility; (II) Evolve system w/ improved technologies; (III) Develop one or more systems to TRL 6 before start of flight development; and (IV) Flight development for Outpost. To minimize cost and ensure that ISRU technologies, systems, and functions are integrated properly into the Outpost, technology development efforts are being coordinated with other development areas such as Surface Mobility, Surface Power, Life Support, EVA, and Propulsion. Lastly, laboratory and field system-level tests and demonstrations will be performed as often as possible to demonstrate improvements in: Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness). This presentation will provide the status of work performed to date within the NASA ISRU project with respect to technology and system development and field demonstration activities, as well as the current strategy to implement ISRU in future robotic and human lunar exploration missions.

NASA
In-Situ Resource Utilization (ISRU)
Technology and Development Project Overview

Presentation to the
Space Technology Applications International Forum
Feb. 11, 2008

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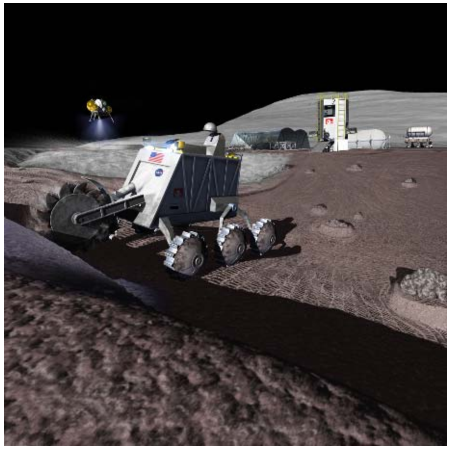
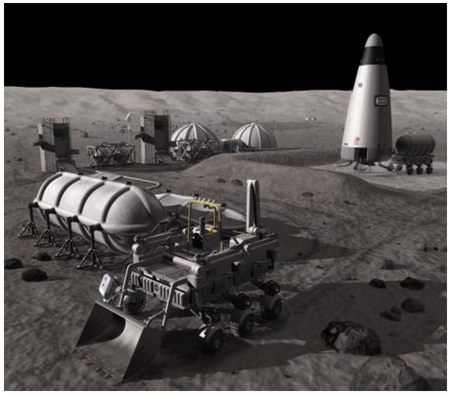
ISRU: Decisions from Lunar Architecture Development



- ISRU is a critical capability and key implementation of the VSE and sustained human exploration
- At the same time, ISRU on the Moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven



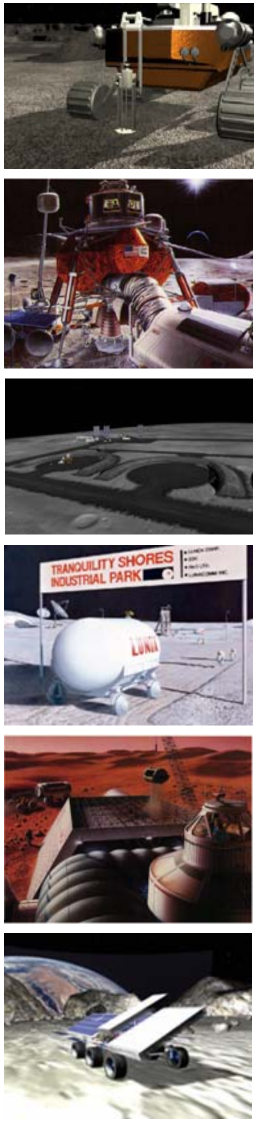
- Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate
- Architecture is designed to be open enough to take advantage of ISRU from whatever source when available

Three Pronged Approach to ISRU Development & Incorporation

- **Identify how ISRU fits into Architecture for Sustained human presence on the Moon**
  - Non-critical path initially with fall back strategy
  - Evolutionary with growth in:
    - Capability
    - Criticality
    - Ties to Mars
    - Ties to Space Commercialization
- **Build confidence in ISRU early and often**
  - Multiple generations of hardware and systems developed
  - Extensive ground and analog site testing for operations, maintenance, and interconnectivity
  - Robotic precursors if possible to reduce risk AND
    - Tie to common science objectives for regolith, mineral, and volatile characterization
    - Tie to long-term operations associated with Outpost deployment and operation
- **Early NASA involvement in all aspects of ISRU with transition to industry**
  - Ensures NASA is ‘smart’ buyer
  - Ensures lessons learned from ground and flight demonstrations are transferred to all of industry (unless pre-agreement established for commercialization aspect)
  - Ensures long-term industry involvement

What is Lunar In-Situ Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration



In-Situ Lunar Resources

- **‘Natural’ Lunar Resources:**
  - Regolith, minerals, metals, volatiles, and water/ice
  - Sunlight, vacuum, thermal gradients/cold sinks
- **Discarded Materials**
  - LSAM descent stage fuel residual scavenging, tanks, etc. after landing (with Power)
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services (Lunar Architecture Team findings)

- **Site Preparation and Outpost Deployment/Emplacement**
  - Site surveying and resource mapping
  - Crew radiation protection (In-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  - Area and road clearing to minimize risk of payload delivery and emplacement
- **Mission Consumable Production**
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O_2) and water
  - Propellant production for robotic and human vehicles
  - Regenerate and storage life support and fuel cell power consumables (in conjunction with Life Support and Power)
- **Outpost Growth and Self-Sufficiency**
  - Fabrication of structures that utilize in-situ materials (in conjunction with Habitats)
  - Solar array, concentrator, and/or rectenna fabrication (in conjunction with Power)
  - Thermal energy storage & use from processed regolith (in conjunction with Power)
  - Production of feedstock for fabrication and repair (in conjunction with Sustainability)

ISRU Consumable Production for Lunar Architecture

- **O_2 Production from Regolith**
  - 2 MT/yr production rate for surface mission consumables – 1 MT/yr for ECLSS/EVA and 1 MT/yr to make water
  - Capability manifested on 6th landed mission (before start of permanent presence)
  - Increased production to 10 MT/yr during Outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability

- **In-Situ Water Production**
  - Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
  - Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O_2 & H_2) production is required

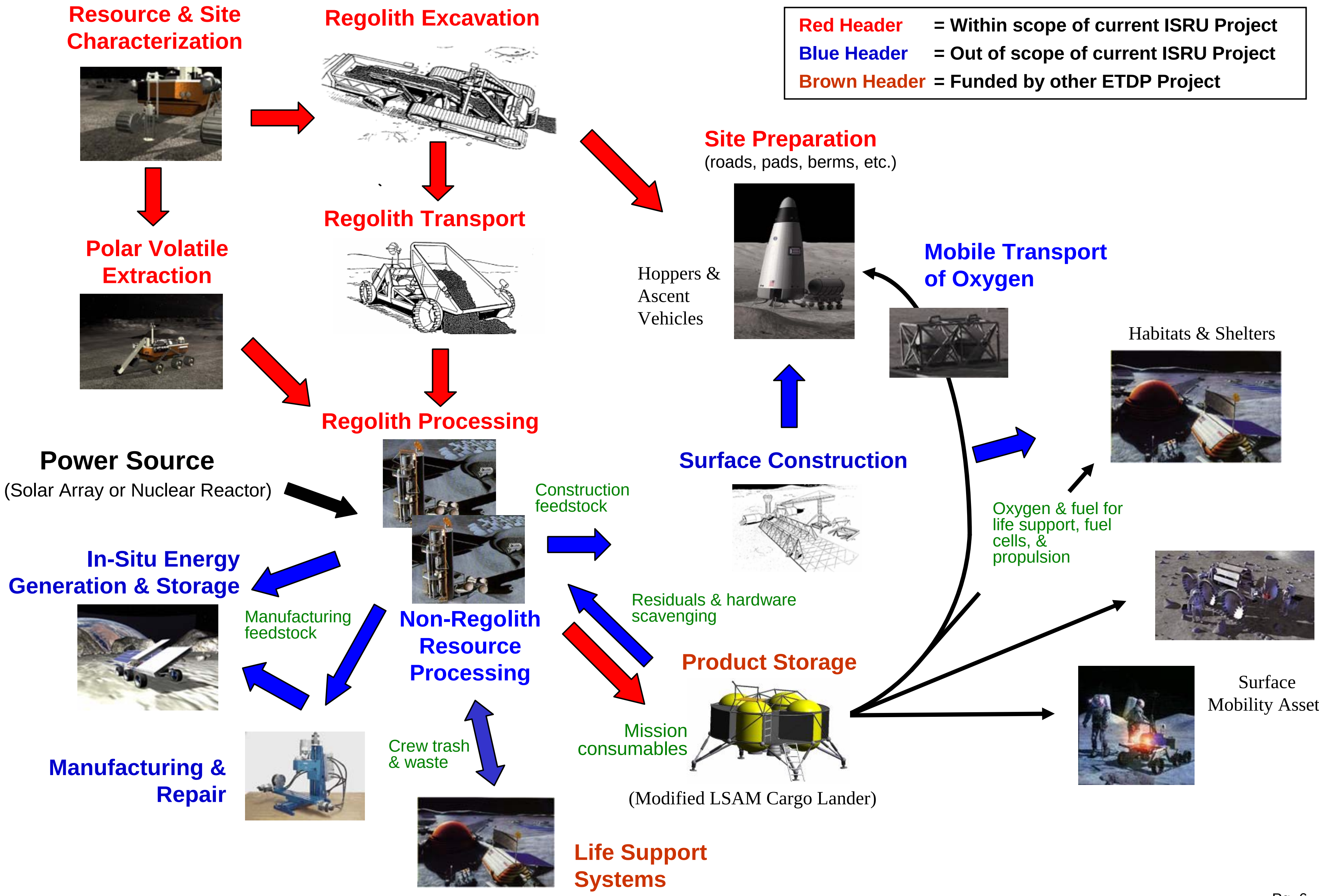
- **In-Situ Methane Production**
  - Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
  - Capability supports LSAM Ascent 'top-off' in case of leakage, power loss, or increased payload to orbit

ISRU Processing Requirements	**kg/yr (min.)**
Oxygen Production	
For ECLSS & EVA	1000
For Water Production	800
For LSAM Ascent Propulsion	7600
Water Production	
For ECLSS & EVA (from in-situ O_2 + Scavenged H_2)	900
Required H_2 Scavenged from LSAM Descent Stage	100
For radiation shielding (*one time production need)	1000 to 2000*
Water Electrolysis	
For ISRU	1125
For Night time Power	7335
For Pressurized Rover Power (45 kg/mission)**	1260
Methane Production	
For LSAM Ascent Propulsion (max)	2160

** 28 excursions per year with at least 1 MPU

ISRU - Related Surface Elements & Activities

Red Header	= Within scope of current ISRU Project
Blue Header	= Out of scope of current ISRU Project
Brown Header	= Funded by other ETDP Project



Resource & Site Characterization

Regolith Excavation

Polar Volatile Extraction

Regolith Transport

Site Preparation

(roads, pads, berms, etc.)

Hoppers & Ascent Vehicles

Mobile Transport of Oxygen

Habitats & Shelters

Regolith Processing

Power Source

(Solar Array or Nuclear Reactor)

Construction feedstock

Surface Construction

Oxygen & fuel for life support, fuel cells, & propulsion

In-Situ Energy Generation & Storage

Manufacturing feedstock

Non-Regolith Resource Processing

Residuals & hardware scavenging

Product Storage

Surface Mobility Asset

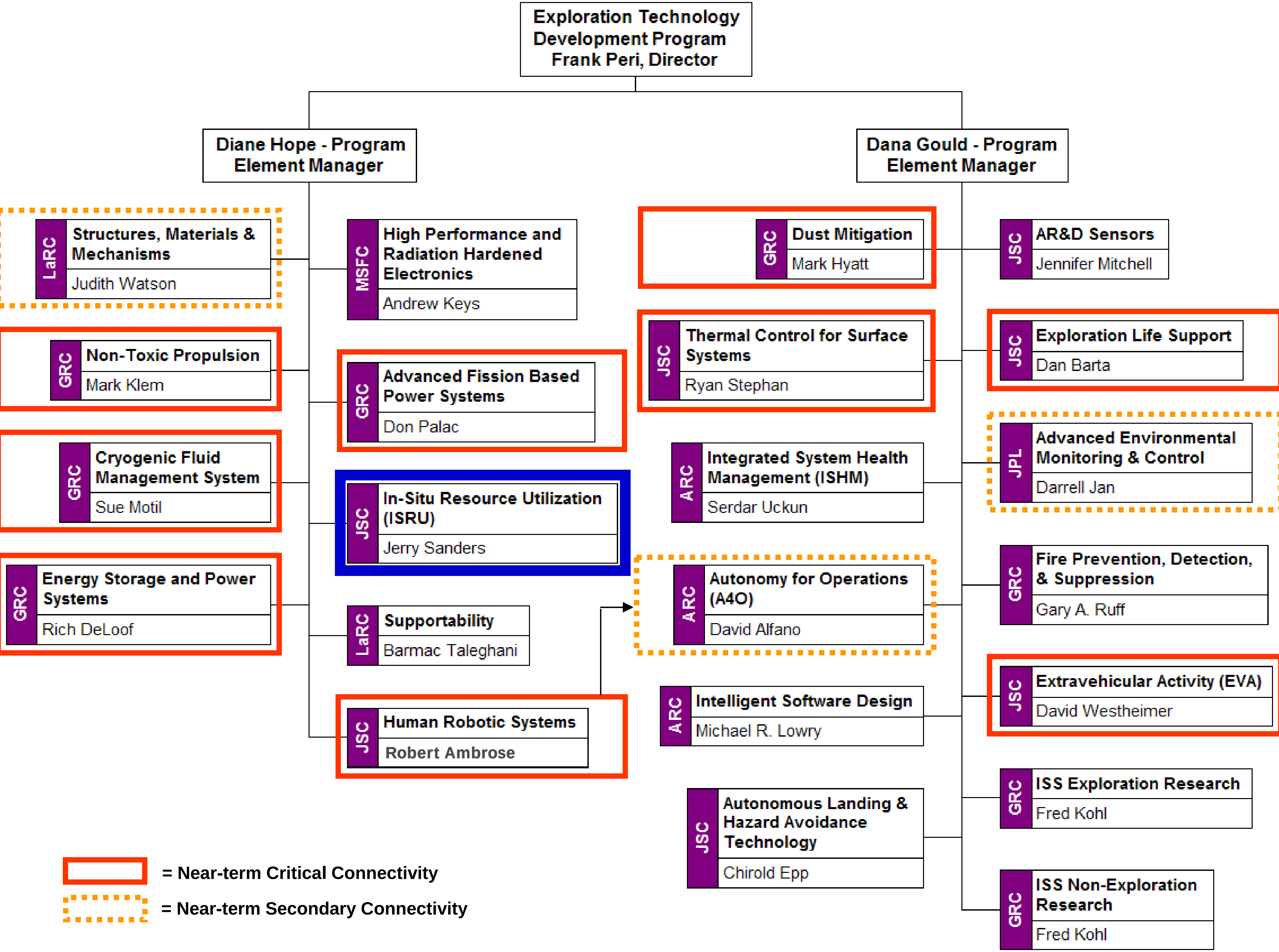
Mission consumables

Crew trash & waste

Manufacturing & Repair

(Modified LSAM Cargo Lander)

Life Support Systems



Exploration Technology Development Program
Frank Peri, Director

Diane Hope - Program Element Manager

- LaRC **Structures, Materials & Mechanisms** — Judith Watson
- GRC **Non-Toxic Propulsion** — Mark Klem
- GRC **Cryogenic Fluid Management System** — Sue Motil
- GRC **Energy Storage and Power Systems** — Rich DeLoof
- MSFC **High Performance and Radiation Hardened Electronics** — Andrew Keys
- GRC **Advanced Fission Based Power Systems** — Don Palac
- JSC **In-Situ Resource Utilization (ISRU)** — Jerry Sanders
- LaRC **Supportability** — Barmac Taleghani
- JSC **Human Robotic Systems** — **Robert Ambrose**

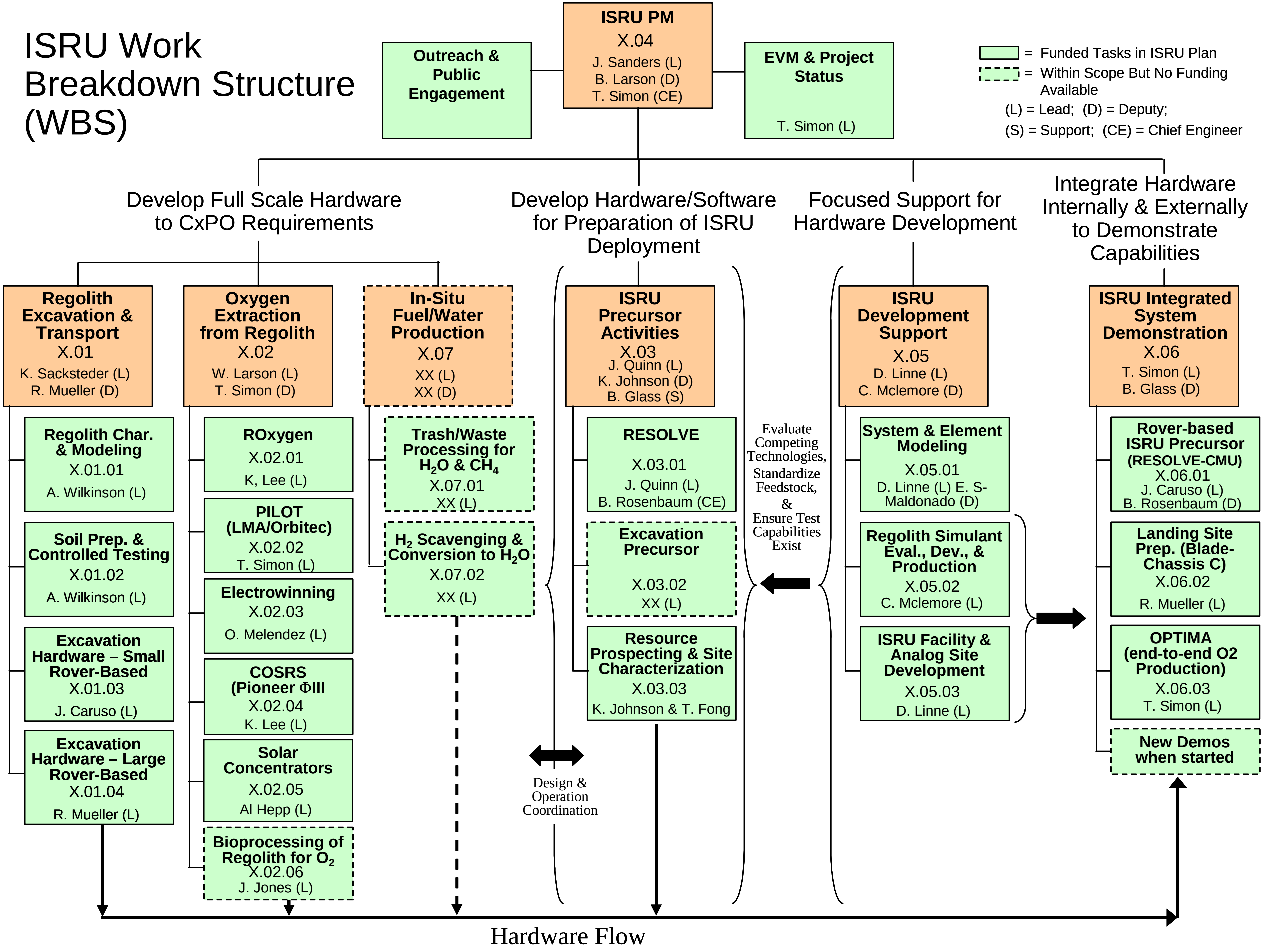
Dana Gould - Program Element Manager

- GRC **Dust Mitigation** — Mark Hyatt
- JSC **Thermal Control for Surface Systems** — Ryan Stephan
- ARC **Integrated System Health Management (ISHM)** — Serdar Uckun
- ARC **Autonomy for Operations (A4O)** — David Alfano
- ARC **Intelligent Software Design** — Michael R. Lowry
- JSC **Autonomous Landing & Hazard Avoidance Technology** — Chirold Epp
- JSC **AR&D Sensors** — Jennifer Mitchell
- JSC **Exploration Life Support** — Dan Barta
- JPL **Advanced Environmental Monitoring & Control** — Darrell Jan
- GRC **Fire Prevention, Detection, & Suppression** — Gary A. Ruff
- JSC **Extravehicular Activity (EVA)** — David Westheimer
- GRC **ISS Exploration Research** — Fred Kohl
- GRC **ISS Non-Exploration Research** — Fred Kohl

□ **= Near-term Critical Connectivity**

⬚ **= Near-term Secondary Connectivity**

ISRU Work Breakdown Structure (WBS)



🟩 = Funded Tasks in ISRU Plan
⬚ = Within Scope But No Funding Available
(L) = Lead; (D) = Deputy;
(S) = Support; (CE) = Chief Engineer

ISRU PM
X.04
J. Sanders (L)
B. Larson (D)
T. Simon (CE)

Outreach & Public Engagement

EVM & Project Status
T. Simon (L)

Develop Full Scale Hardware to CxPO Requirements

Regolith Excavation & Transport
X.01
K. Sacksteder (L)
R. Mueller (D)

- **Regolith Char. & Modeling**
  X.01.01
  A. Wilkinson (L)
- **Soil Prep. & Controlled Testing**
  X.01.02
  A. Wilkinson (L)
- **Excavation Hardware – Small Rover-Based**
  X.01.03
  J. Caruso (L)
- **Excavation Hardware – Large Rover-Based**
  X.01.04
  R. Mueller (L)

Oxygen Extraction from Regolith
X.02
W. Larson (L)
T. Simon (D)

- **ROxygen**
  X.02.01
  K, Lee (L)
- **PILOT (LMA/Orbitec)**
  X.02.02
  T. Simon (L)
- **Electrowinning**
  X.02.03
  O. Melendez (L)
- **COSRS (Pioneer ΦIII**
  X.02.04
  K. Lee (L)
- **Solar Concentrators**
  X.02.05
  Al Hepp (L)
- **Bioprocessing of Regolith for O_2**
  X.02.06
  J. Jones (L)

In-Situ Fuel/Water Production
X.07
XX (L)
XX (D)

- **Trash/Waste Processing for H_2O & CH_4**
  X.07.01
  XX (L)
- **H_2 Scavenging & Conversion to H_2O**
  X.07.02
  XX (L)

Develop Hardware/Software for Preparation of ISRU Deployment

ISRU Precursor Activities
X.03
J. Quinn (L)
K. Johnson (D)
B. Glass (S)

- **RESOLVE**
  X.03.01
  J. Quinn (L)
  B. Rosenbaum (CE)
- **Excavation Precursor**
  X.03.02
  XX (L)
- **Resource Prospecting & Site Characterization**
  X.03.03
  K. Johnson & T. Fong

Design & Operation Coordination

Evaluate Competing Technologies, Standardize Feedstock, & Ensure Test Capabilities Exist

Focused Support for Hardware Development

ISRU Development Support
X.05
D. Linne (L)
C. Mclemore (D)

- **System & Element Modeling**
  X.05.01
  D. Linne (L) E. S-Maldonado (D)
- **Regolith Simulant Eval., Dev., & Production**
  X.05.02
  C. Mclemore (L)
- **ISRU Facility & Analog Site Development**
  X.05.03
  D. Linne (L)

Integrate Hardware Internally & Externally to Demonstrate Capabilities

ISRU Integrated System Demonstration
X.06
T. Simon (L)
B. Glass (D)

- **Rover-based ISRU Precursor (RESOLVE-CMU)**
  X.06.01
  J. Caruso (L)
  B. Rosenbaum (D)
- **Landing Site Prep. (Blade-Chassis C)**
  X.06.02
  R. Mueller (L)
- **OPTIMA (end-to-end O2 Production)**
  X.06.03
  T. Simon (L)
- **New Demos when started**

Hardware Flow

NASA Participants in Lunar ISRU Development

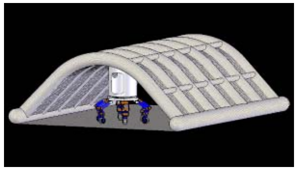
- **JSC – Project & ISRU Integration Lead**
  - ISRU management and system modeling
  - ROxygen and ROE hydrogen reduction oxygen extraction from regolith design and laboratory testing
  - Lunar material science & handling (KA)
  - Lunar simulant development support (KA)
  - ISRU integrated and field demonstration lead
  - ISRU Small Business Innovative Research (SBIR) topic and subtopic leads
- **KSC – Oxygen Production Lead**
  - Regolith & Environmental Science and Oxygen & Lunar Volatile Extraction (RESOLVE); Lead and Sample collection, volatile chamber, and water/hydrogen collection and processing
  - Regolith electrolysis oxygen production modeling and laboratory testing
  - Lunar regolith excavation modeling and development support; lead for large-rover based
  - ISRU SBIR subtopic support
- **MSFC – Simulant Development Lead**
  - Lunar simulant development
  - Regolith electrolysis oxygen production modeling and laboratory testing
  - Solar concentrator for oxygen production
  - ISRU SBIR subtopic support
- **GRC – Excavation & Transport Lead**
  - Lunar-g particle and material behavior modeling and testing
  - Regolith excavation and material transport modeling, development and laboratory testing; lead for small-rover based
  - Oxygen extraction from regolith modeling & research
  - RESOLVE volatile oven
  - Solar concentrator for oxygen production
  - ISRU SBIR subtopic support
- **JPL – Instrument & Resource Prospecting Lead**
  - System and architecture modeling
  - RESOLVE – regolith chemical and physical characterization; regolith thermal probe
  - In-situ instruments and sensors for resource and site assessment
- **ARC – Site Characterization & SMD Involvement**
  - Mars science drilling and subsurface exploration expertise
  - Site characterization & resource prospecting instrumentation and mapping hardware and software
  - Rover/arm integration and operations with ISRU

Possible Excavation Needs & Requirements for the Outpost

- **Excavation for Oxygen Production**
  - Evaluated a number of excavation options
  - Parametrics presented are based on a front-end/overshot loader that scoops and dumps into bin on back of chassis
  - If operate continuously, primary difference between small and large chasses is rate of drain on battery
    - Very inefficient to dig slowly/small amounts per scoop - lifting arm and dumping into bin is primary energy drain

- **Excavation for Outpost: Landing pads and berms**
  - Largest outpost emplacement excavation requirement over life of Outpost
  - If landers are not moved, a new pad needs to be prepared *every 6 months*
  - Capability Manifested on 1st landed mission

- **Excavation for Outpost: Habitat protection**
  - Multiple options if regolith shielding for radiation or thermal is desired
  - Trenching and inflatable covers evaluated for excavation impact



- **Excavation for Outpost Emplacement**
  - Excavate ramp or hole for nuclear reactor emplacement/shielding
  - Prepare pathways for transferring cargo from lander
  - Prepare trenches for cables

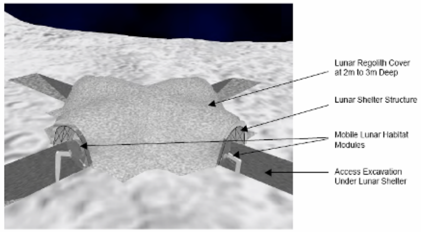


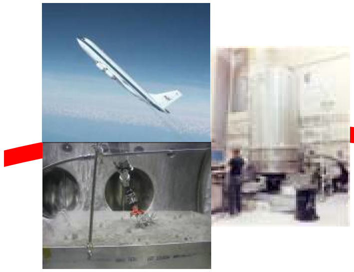
FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules.

- **Excavation for Science**
  - Prepare trenches for subsurface geologic/strategraphy access for Science
  - Core extraction drilling for subsurface sample acquisition (resource characterization)
  - Site preparation for antenna deployment

Integrated Approach to Lunar Excavation & Material Handling Development

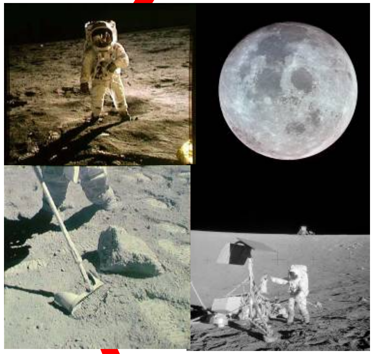
Develop Ability to Simulate Lunar Conditions

- Lunar Regolith Simulant Test Bins for different locations and depths
- Thermal/Vacuum Chambers
- Partial-Gravity Parabolic Aircraft
- Radiation/Dust Exposure



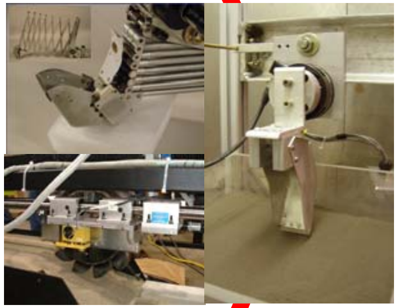
Develop and Test Hardware Under Controlled Conditions

- Ground support equipment to measure, forces and torques, and power
- Implements to understand regolith /hardware interaction for modeling Implements to examine excavation and material transport concepts



Known Lunar Environment & Hardware Operation Data

- Surveyor Telemetry
- Apollo Crew Measurements
- Returned Lunar Samples
- Clementine/Lunar Prospector/Lunar Reconnaissance Orbiter



Model Regolith Properties & Hardware/Regolith Interactions

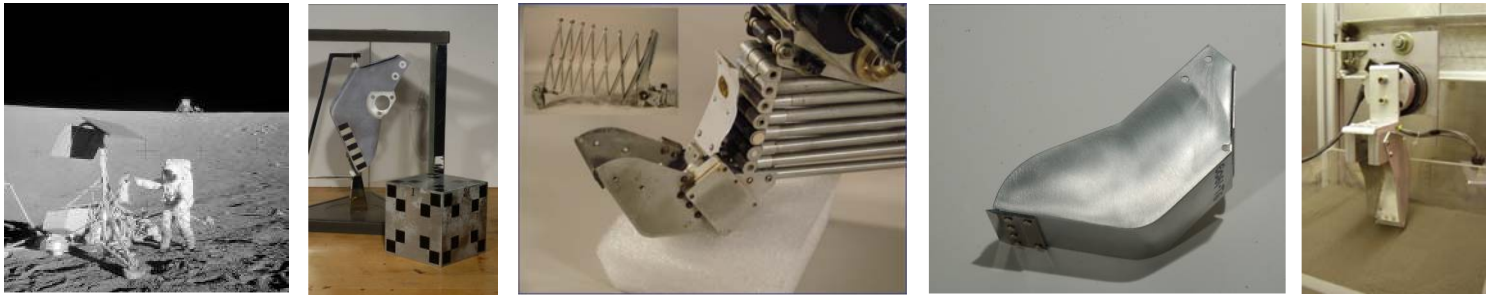
Lunar Regolith Simulant Particles
  Soil Properties (interacting particles)
    Hardware Concepts (movement/forces)
    Machine/Soil Interactions (force/power)
      Estimate Hardware Performance on the Moon
        End to End ISRU System Models

Develop and Test Hardware & Operations For Mission Needs

- Integrate and test implements on rovers
- Interaction of regolith handling and transport with other subsystems
- Automation and logistics
- Operation planning, coordination, and execution

Lunar Regolith Excavation Development

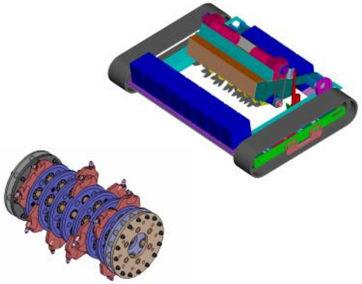
Soil Preparation and Controlled Testing



Surveyor Arm/Scoop Re-fabrication and Controlled Laboratory Testing at GRC

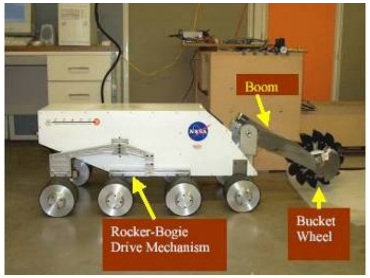
Excavation Hardware – Small Rover-based

Cratos Small Excavator at GRC



Cratos w/ Hard Regolith Cutter Concept

Buckwheel Testing At NORCAT



Bucketwheel Excavator at CSM

Bucketdrum Excavator at LMA (IR&D)

Excavation Hardware – Large Rover-based

Chariot (Chassis C) Vehicle

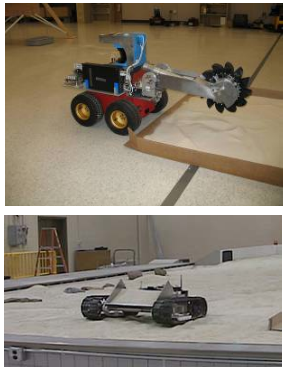
Area Clearing Blade on Chariot

Multi-purpose End-effecter on Chariot

Mobility Platforms for ISRU

Three main ISRU capabilities require different mobility platform attributes

- Site and resource characterization
- Oxygen extraction from regolith
- Site preparation and Outpost emplacement



Small Platforms (<50 kg payload)

Pros

- Lightweight, easy to package multiple units
- Supports Robotic Precursor oxygen extraction systems

Cons

- May not have mass or force to allow deep digging
- or area clearing
- May not have life required for long term operations
- Rocks may be problem

All ISRU-Mobility Platform options need to be evaluated in laboratory and field tests before Final Architecture decisions are made

Medium Platforms (+100 kg payload)

Pros

- Higher mass and force than Small platforms will allow area clearing and berm building
- Easier to package multiple units than Large platforms
- Supports site characterization & Science objectives

Cons

- May be oversized for just oxygen extraction and undersized for extensive site construction

Large Platforms (+1mT kg payload)

Pros

- Good for area clearing, berm building, and hole/trench digging
- Easily meets all early ISRU needs with only fraction of operational time needed

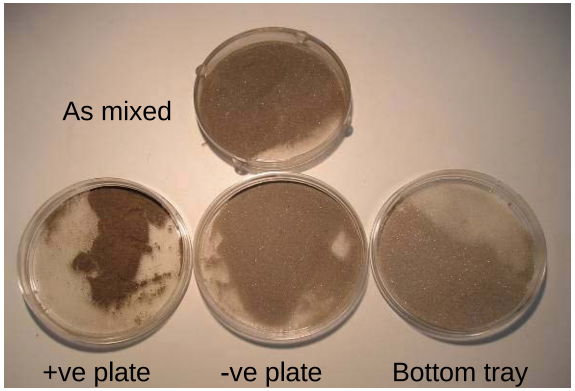
Cons

- Extremely oversized for Outpost O_2 production
- Multiple units represent significant payload mass investment

ISRU Regolith Development, Mitigation, & Handling

Regolith Beneficiation

Regolith Iron-Oxide Beneficiation (KSC)



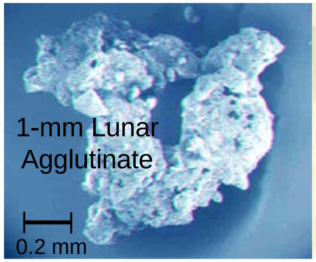
Beneficiated Regolith after 1^{st} Pass (PTFE Charger)

Feldspar: $(Na,K)AlSi_3O_8$;SiO_2	40%
Spodumene: $LiAlSi_2O_6$	40%
Olivine: $(Mg,Fe)_2SiO_4$	10%
Ilmenite: $FeTiO_3$	10%

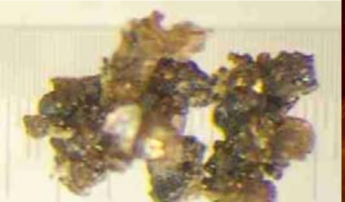
Reade Advanced Materials ~ 300 mesh sieved
Further sieved to 50-75 µm size range

- Important for H_2 Reduction to increase efficiency

Lunar Simulant Development

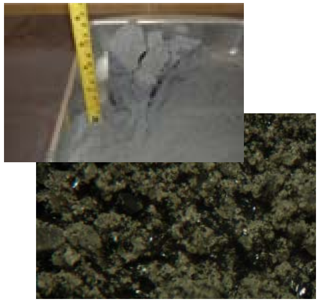


1-mm Lunar Agglutinate

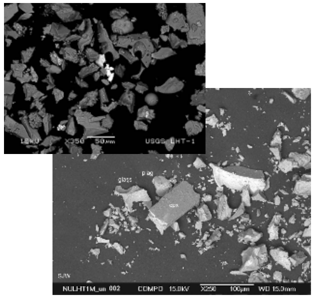


Artificial Agglutinate- from JSC1a (ORBITEC)

Glass Agglutinate- from LHT (USGS)



OB1 Highland Simulant (NORCAT/UNB)



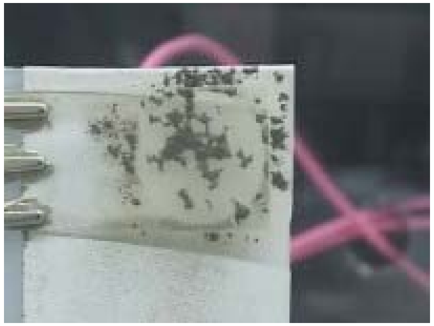
Lunar Highland (LHT) Simulant (MSFC-USGS)

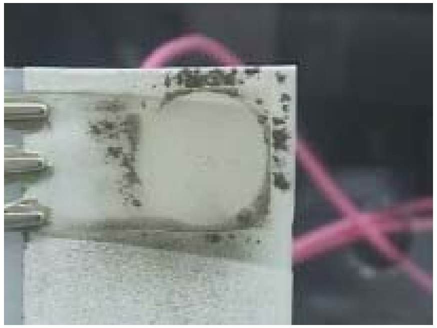
JSC1a (ORBITEC)

Regolith Mitigation

- Transparent electrodes on glass with lunar simulant; Raman spectrum not attenuated negatively
- Integration of electrode/window into Metering Device/Crusher for RESOLVE EBU#2 now in work

Before activation





After activation

O_2 Production From Regolith Overview & Plans

- **Develop and evaluate the performance of production technologies.**
  - O_2 production in early Outpost can eliminate logistics resupply from Earth, by up to 2 to 4 MT/yr (EVA and life support makeup).
  - Technologies under development range from low yield/low technical difficulty to high yield/high technical difficulty.
  - High yield technologies may reduce the amount of regolith required to make oxygen and ultimately produce usable metals and silicon for in-situ fabrication

- **Oxygen Extraction from Regolith Systems (includes Excavation)**
  - Hydrogen Reduction (~1% extraction efficiency at poles; 5% at equator):
  - Carbothermal Reduction (14 to 28% extraction efficiency)
  - Molten Electrolysis (up to 40%)

- **Develop Prototype Systems for Hydrogen Reduction and Carbothermal Reactors for end-to-end field demonstrations (with excavation) by end of FY08**
  - Scaled for 1 MT/yr O_2 Production Rate
  - Share Common Hardware When Possible (e.g. Water Electrolysis)
  - Prototype will be integrated with Excavation Hardware for a field demonstration at an analog site.
  - Prototypes will operate for a minimum of four hours per day for up to 7 straight days (allows us to study startup and shutdown issues)

- **Investigate Molten Oxide Electrolysis (MOE) for feasibility**
  - MOE has highest yield of all O_2 production technologies
  - MOE can also theoretically produce pure metals
  - Investigations will focus on key technical challenges to insure feasibility (Inert Anode, Cell Design, Materials Feed and Metals Removal)

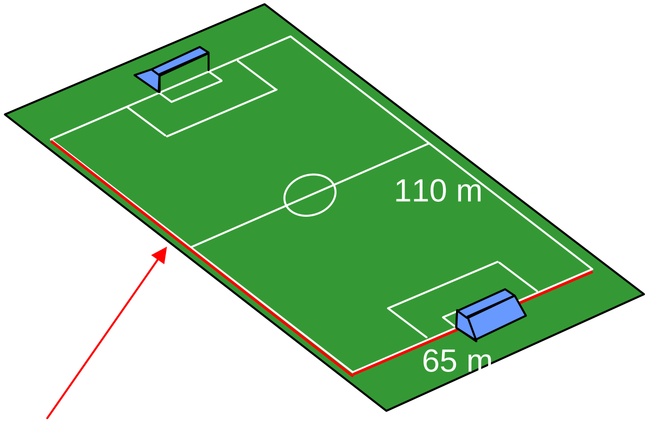
Oxygen Production from Regolith Results (Polar Region)

Polar Outpost - Based on 70% Sunlight/ISRU Operation per year

ISRU System Option	O2 per year (MT)	Mass* (kg)	Subsystem Mass (kg)	Volume* (m3)	Power** (kW)
Hydrogen reduction	1	590	231 - Excavation tools 359 - O2 production & storage	4.6	1.5
	2	791	231 - Excavation tools 560 - O2 production & storage	7.7	2.8
	5	1366	231 - Excavation tools 1135 - O2 production & storage	17.9	7.0
	10	2194	231 - Excavation tools 1963 - O2 production & storage	38.5	15.3
Carbothermal (w/Chassis C)	1	416	75 - Excavation tools 341 - O2 production & storage	3.2	2.2
	2	703	75 - Excavation tools 628 - O2 production & storage	7.2	4.5
	5	1545	75 - Excavation tools 1470 - O2 production & storage	18.5	11.8
	10	2878	75 - Excavation tools 2803 - O2 production & storage	33.9	25.2
Carbothermal (w/2 mini-excavators	2	747	150 - Excavators (2) 597 - O2 production & storage		

* Mass and volume include 20% margin

** Power is electrical power only and includes 10% margin



10 MT of oxygen per year requires excavation of a soccer field to a depth of 0.6 to 8 cm!

(1% & 14% efficiencies)

Vehicle mass: ~80 kg; Regolith load/scoop: ~23 kg

Excavation/deliver: ~150 kg of sand in 10 min.

Conclusions

- All size systems show mass payback in first year of operation, even for low-yield H_2 reduction option
- Carbothermal achieves much higher yield which results in lower mass at lower production rates, but higher thermal energy requirement
  - Higher technology risk than hydrogen reduction

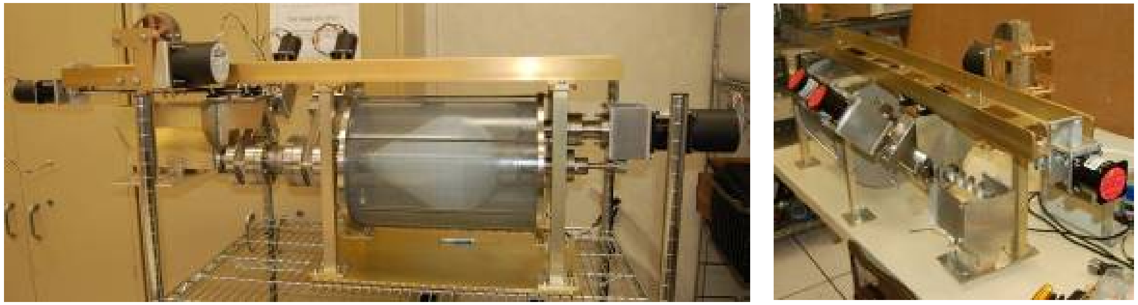
Excavation rates required for 10 MT O_2/yr production

- Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
- Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
- Electrowinning (up to 40%): 4 kg/hr

ISRU O_2 Extraction from Regolith Development

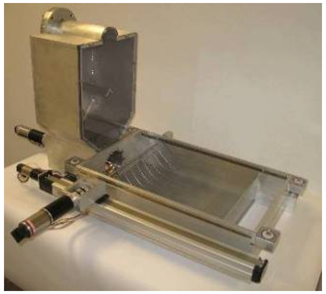
H_2 Reduction Rotating Reactor System (PILOT-LMA)

PILOT Hydrogen Reduction Kinetic Reactor



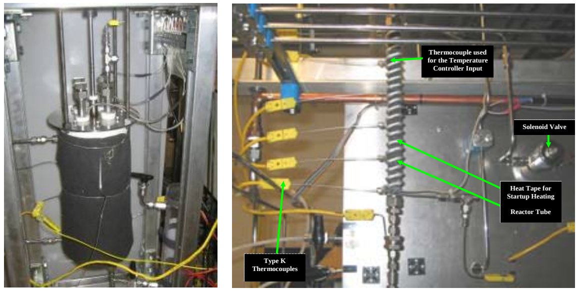
Reactor-Regolith Handling/Transport Testbed

CH_4 Carbothermal Reduction Reactor System (PILOT-ORBITEC)



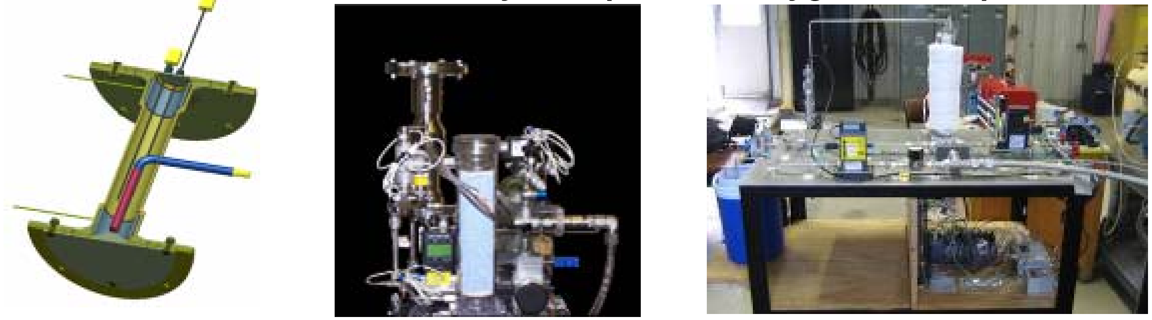
Regolith Handling/Transport Testbed

PILOT Carbothermal Reactor Testbed



Methane Regeneration Reactor

H_2 Reduction Fluidized-Bed Reactor System (ROE & ROxygen - NASA)



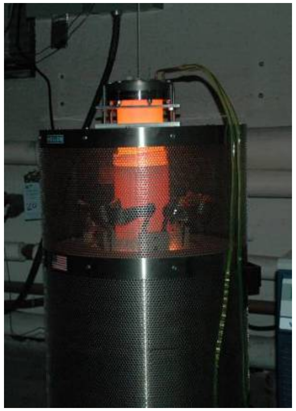
Hydrogen Reduction Fluidized Subscale Reactor Testbed

Water Electrolysis Breadboard

ISRU O_2 Extraction from Regolith Development (Cont.)

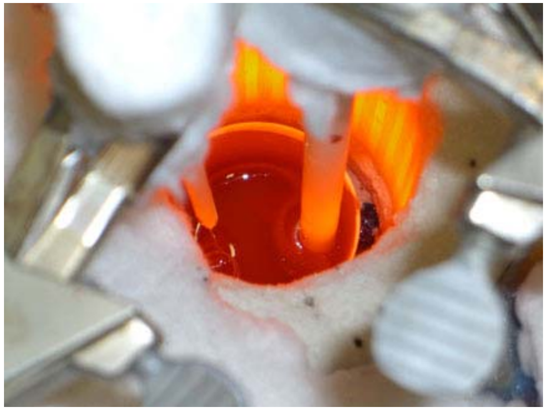
Regolith Salt & Molten Electrolysis

Ilmenox (FFC Process)
Cell at FIT



Molten Electrolysis
Cell at MIT

Low-Temperature
Electrolysis Cell at KSC



Early Electrolysis Cell Test
at MSFC

Outpost O_2 Extraction Plant Concept
with Solar Concentrator & O_2 Storage

Fully raised position

Fully lowered position

Robotic Precursor O_2 Extraction Plant
Concept with Micro Excavator (LMA)

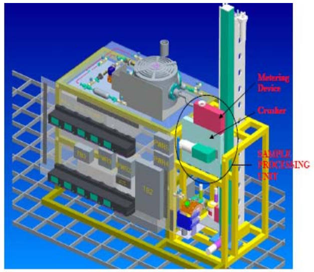
Robotic Precursor O_2
Extraction Subscale Demo

Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) Overview

RESOLVE will incorporate five experiment modules from three NASA institutions; JSC, KSC, JPL

- Support from GRC & MSFC
- Drill and excavation expertise from Northern Centre for Advanced Technology (NORCAT)
- Significant university and Lunar science expertise

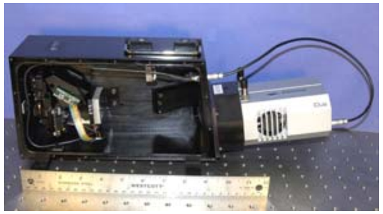
RESOLVE
EBU1



The five RESOLVE modules are:

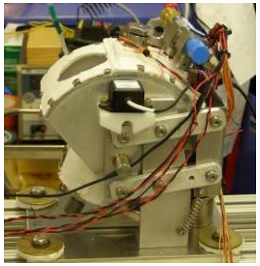
- **EBRC - Excavation and Bulk Regolith Characterization (KSC/NORCAT/CSM)**
  Provide capability of extracting samples of regolith down to 1 meter and determine geo-technical characteristics of the regolith.

- **ROE - Regolith Oxygen Extraction (JSC/GRC)**
  Demonstrate the ability to chemically extract oxygen from the regolith samples.



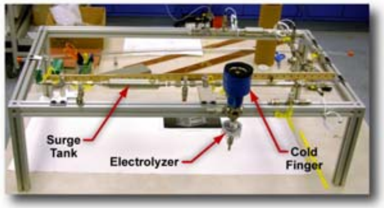
- **ERPC - Environment and Regolith Physical Characterization (JPL)**
  Determine the particle size, shape, color, and chemical characteristics of regolith samples and the regolith temperature in the permanently shadowed crater

- **RVC - Regolith Volatile Characterization (KSC/GRC)**
  Provide capability of evolving and measuring volatiles from regolith samples to determine the form and concentration of hydrogen-bearing molecules in shadowed regions near the lunar poles. Also, determine other volatiles of interest.



RESOLVE Target Design

- Mission Design Life = 7 days in shadowed crater
- Mass < 80 kg
- Max. Power < 200 Watts

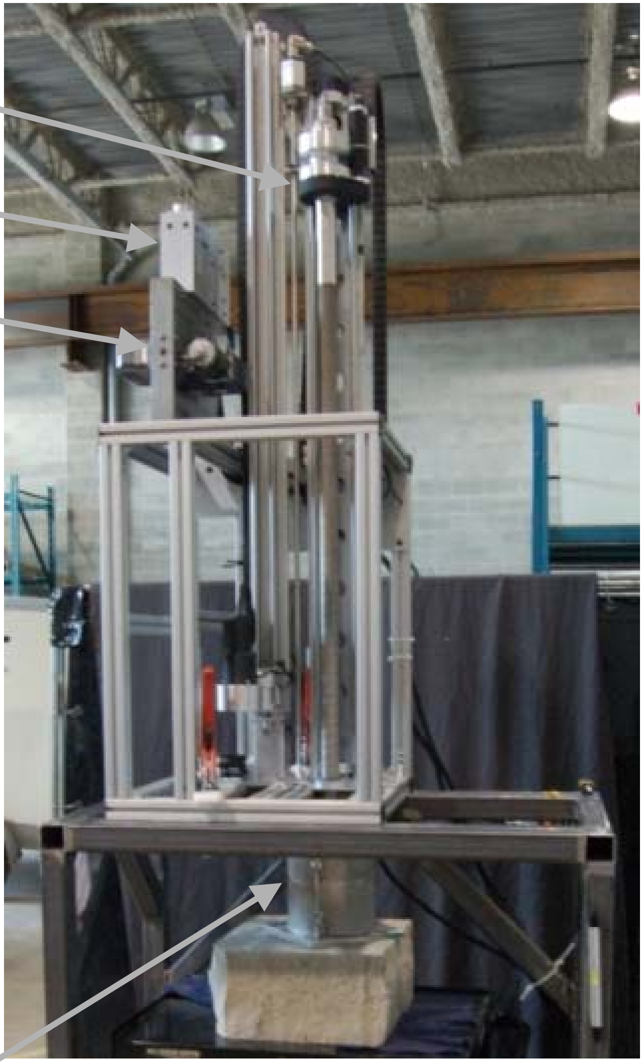


- **LWRD – Lunar Water Resource Demonstration (KSC)**
  Demonstrate the ability to capture and quantify water and hydrogen produced/evolved by the ROE and/or RVC from the regolith samples. In addition the LWRD shall split the water that is captured into hydrogen and oxygen using electrolysis

Drill, Metering Device, & Crusher (EBRC) Accomplishments

Drill, Sample Transfer, Metering Device, & Crusher Assembly (NORCAT)

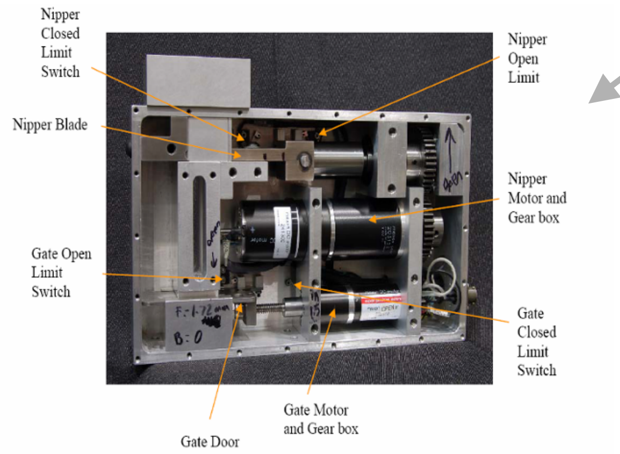
- ✓ Demonstrated the acquisition of 1 meter deep samples in unconsolidated and cryogenic regolith/water mixture
- ✓ Demonstrated transfer of core to metering device
- ✓ Demonstrated metering length of sample and cutting sample
- ✓ Demonstrated crushing samples to 1 millimeter particle sizes

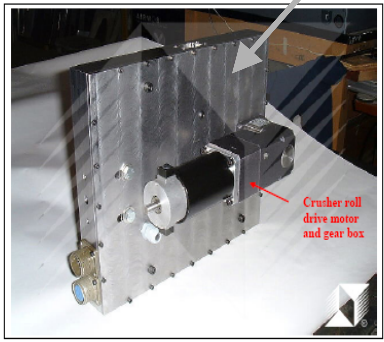


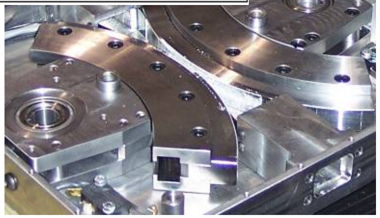
Drill & Sample Transfer

Metering Device

Crusher





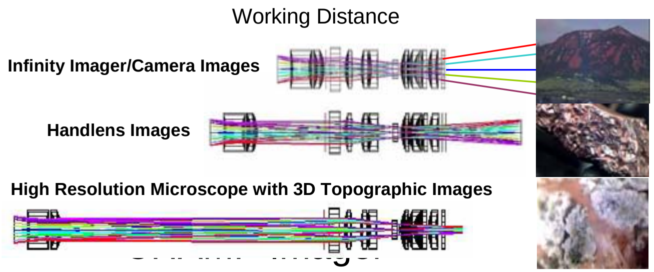


Simulant Chamber for Extraction

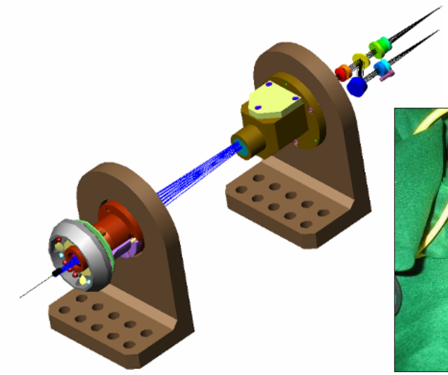
NORCAT: Northern Centre for Advanced Technology

Raman/CHAMP Instrument EBU1 Layout

- ✓ **CHAMP optical design complete for far-field, 30 μ/pixel hand lens, and 3 μ/pixel microscope (with color & UV light)**
- ✓ **Raman Spectroscopy capability designed to yield chemical/mineral content measurements to within 1 wt% per compound including the identification of any hydrogen compounds that are present**
- ✓ **Hardware built and in assembly**

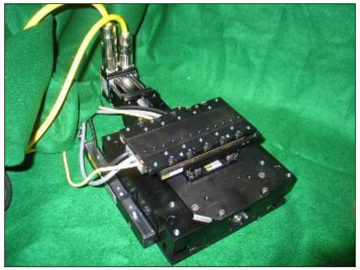


Far-field to Microscope Optics Design

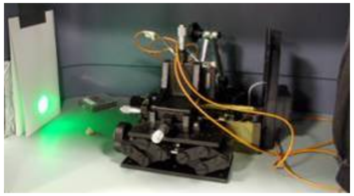


This is a 3D representation that illustrates the current details of the mounting interfaces of Lens Cells #1 and #2.

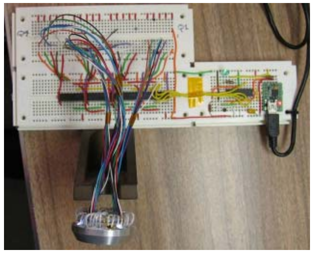
Translation Stage for Raman/CHAMP EBU1

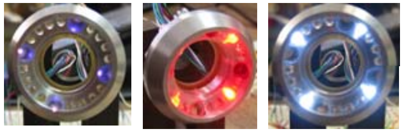


Integrated CHAMP/MMRS breadboard



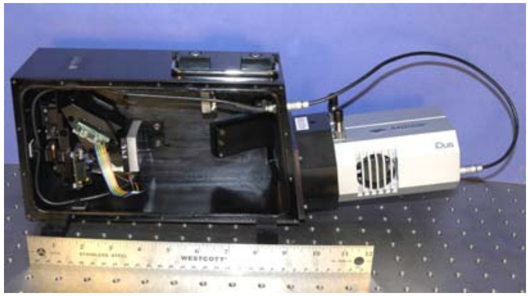
MIDP CHAMP Imager



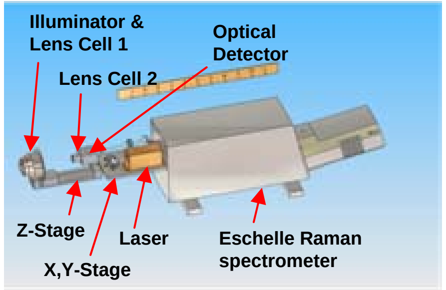


UV LEDs illuminated
Red LEDs illuminated
White LEDs illuminated

CHAMP Illuminator



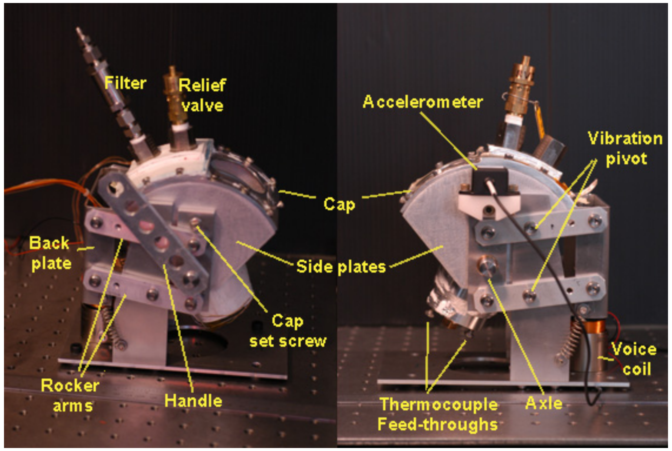
Eschelle Raman Spectrometer for EBU1



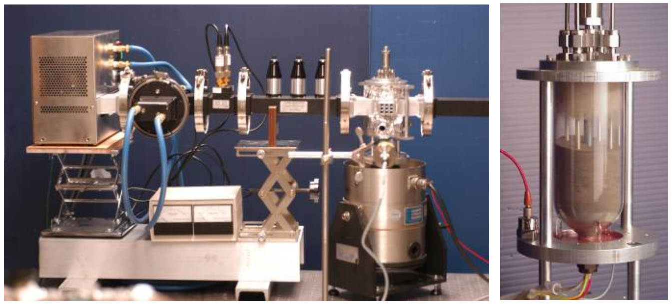
Instrument Layout for Raman/CHAMP EBU1

Regolith Volatile Chamber (RVC) and Gas Chromatograph

- ✓ **Heating chamber built and tested to investigate vibro-fluidization amplitude/frequency, vacuum and microwave heating**
- ✓ **Successfully met the objective of heating simulant (150 C) to release and capture ~1 gram of hydrogen and water**
- ✓ **Successfully measured volatile gas species and quantity characteristics:**
  - Detection limits: 0-20% water (0.05 wt% in regolith), 10 PPM Hydrogen & Helium; Modified to also separate and detect CO, CO_2, CH_4, O_2 and H_2S

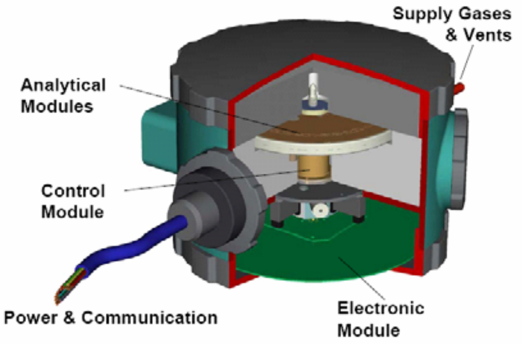


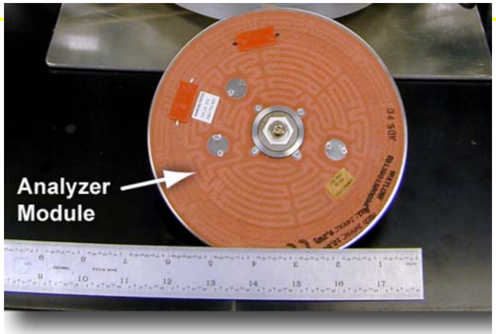
RVC EBU#1 Oven

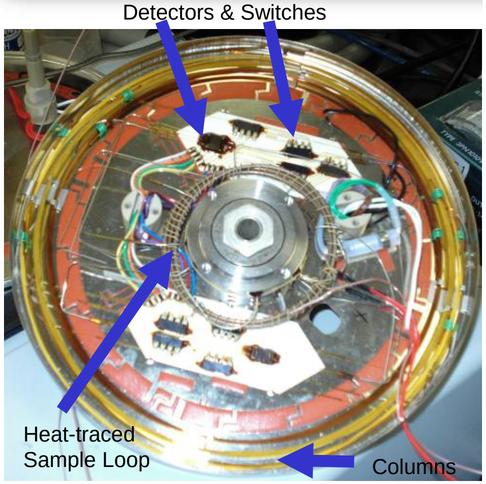


Vibro-fluidization test stand with microwave heating at GRC

Siemens MicroSAM GC



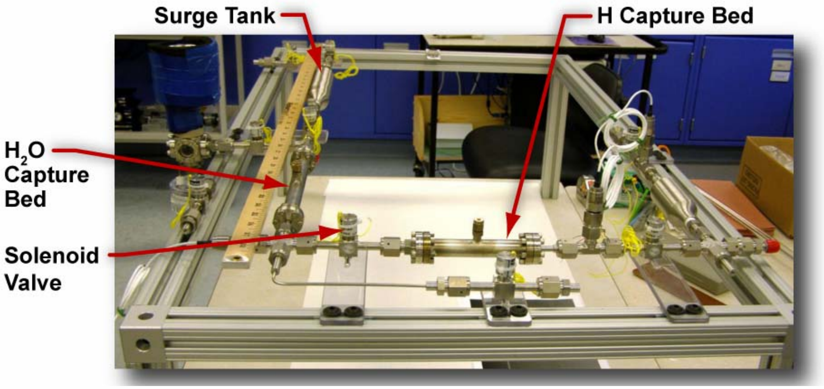


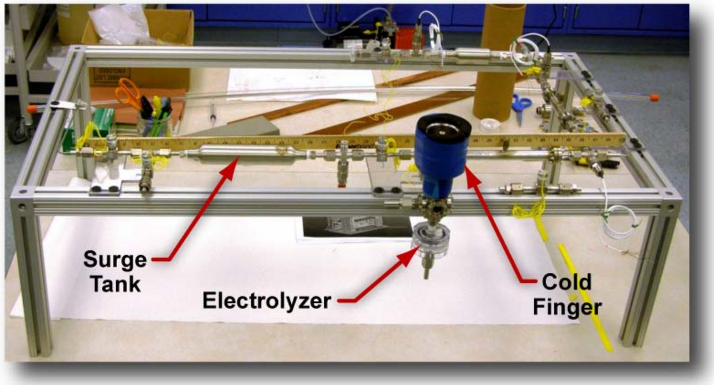


Customized GC Module Work Performed at KSC

Lunar Water Resource Demonstration (LWRD) Accomplishments

- ✓ **Both Water Capture and Hydrogen Capture beds successfully tested.**
- ✓ **Quantification via temperature and pressure measurement currently only accurate to within 30%; Desire 10%**
- ✓ **Successfully performed water droplet freeze/thaw visualization (Public Outreach)**
- ✓ **Water droplet successfully electrolyzed**



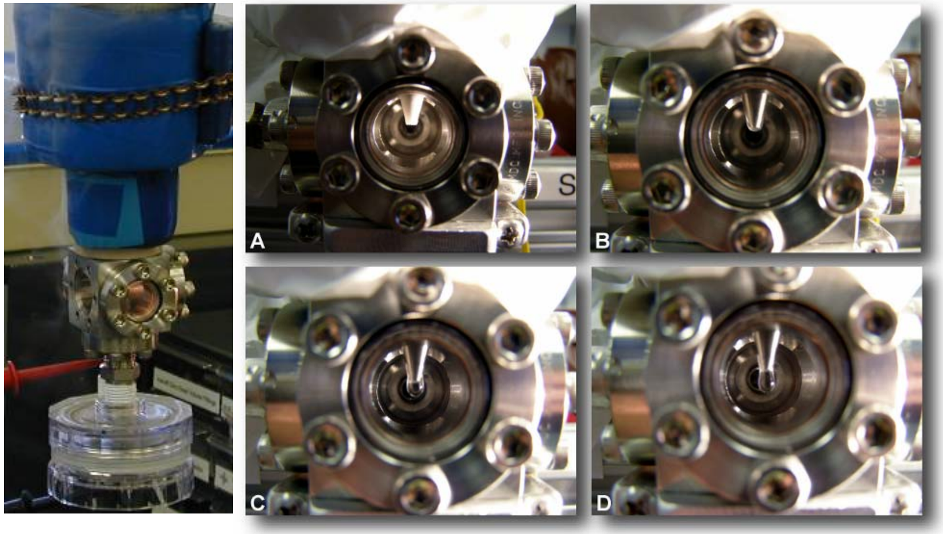



$BaCl_2$ in air 25 hrs at RT


$BaCl_2$ after heating in 400 C


Hydrated Salt Holder

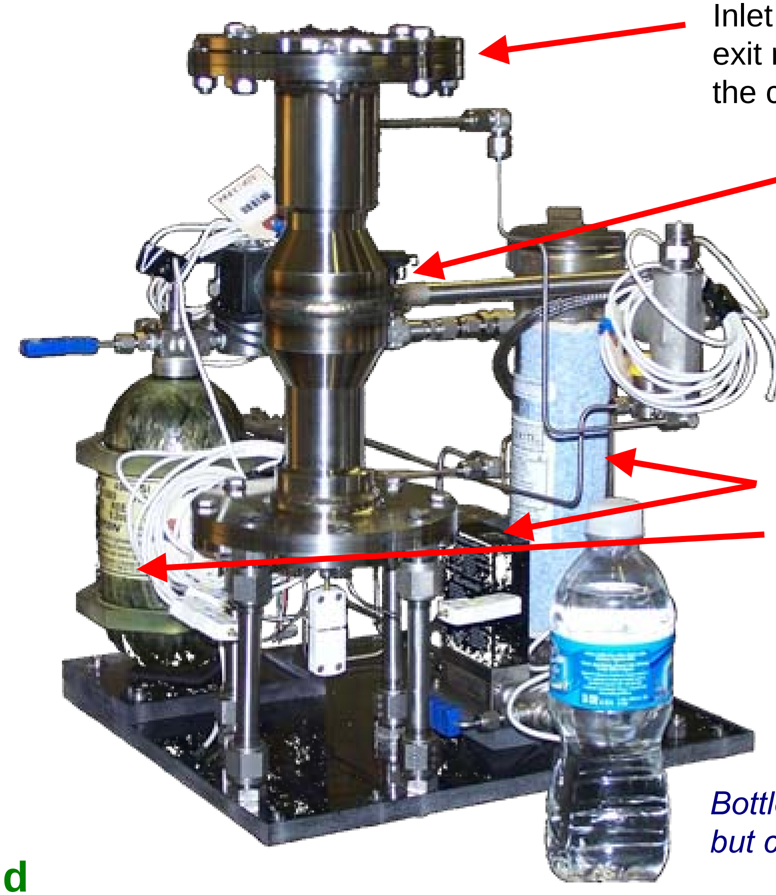
Water Droplet Demonstration



Regolith Oxygen Extraction (ROE) Accomplishments

Oxygen Extraction From Regolith Demonstration System

- ✓ **Successfully met the objective of 1 gram of oxygen extracted per 100 grams of regolith.**
- ✓ **Successfully proved dust filtration, and regolith fluidization and heating.**
- ✓ **Successfully proved system design and approximate volume and power goals.**
- ➢ **Future plans include realistic sealing for regolith inlet/outlet and reduced system & reactor mass.**



Inlet & outlet doors with realistic gas feed & exit methods that allow dirt to fall in & out of the chamber

Realistic reactor chamber, heating method, & fluidization of the regolith for thermal mixing & product removal

Commercial off-the-shelf water capture bed, pump, instrumentation, and hydrogen storage tank

Bottle of water not included but can be produced ☺

H_2 Kinetic Reaction Characterization Testbed

RESOLVE – Rover Integration

- **Objectives**:
  - Demonstrate a mobility system for polar and dark operations
  - Demonstrate rover-based RESOLVE operations for drilling and characterizing lunar resources/ice and demonstrating oxygen extraction from regolith
- **Description**:
  - The RESOLVE engineering breadboard (EBU1) drill is mounted on the Carnegie Mellon Univ. (CMU) Scarab rover. The rover autonomously drives in the dark to a sampling location in FY07. The RESOLVE drill is used to acquire a core sample of ‘lunar regolith’.
  - In FY08 a complete 2nd generation RESOLVE EBU#2 is attached to the CMU Scarab rover. The drill extracts a core and transfers it to the RESOLVE crusher and oven. The rover drives to a new sampling location. All RESOLVE operations are demonstrated.

- **FY07** - Field tests

  Local field demo September 07:
  - Operate drill with CMU Scarab rover

  Local field demo December 07:
  - Operate drill with CMU Scarab rover
  - Operate Scarab with Dark Operations software
- **FY08**

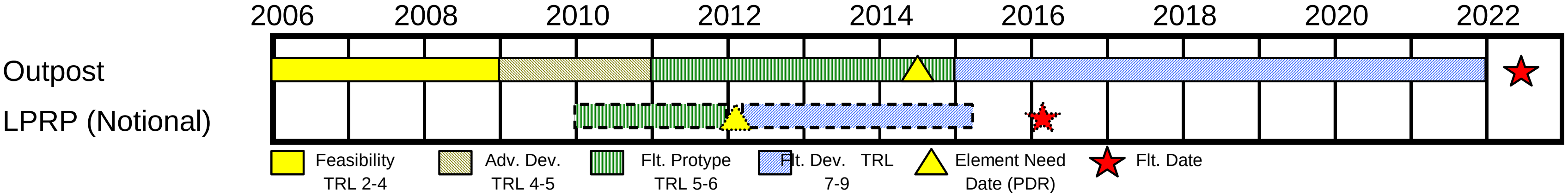
  Upgrade both rover and RESOLVE system (EBU2) and test at remote site
- **FY09**

  Upgrade system with additional science and mobility/navigation assets

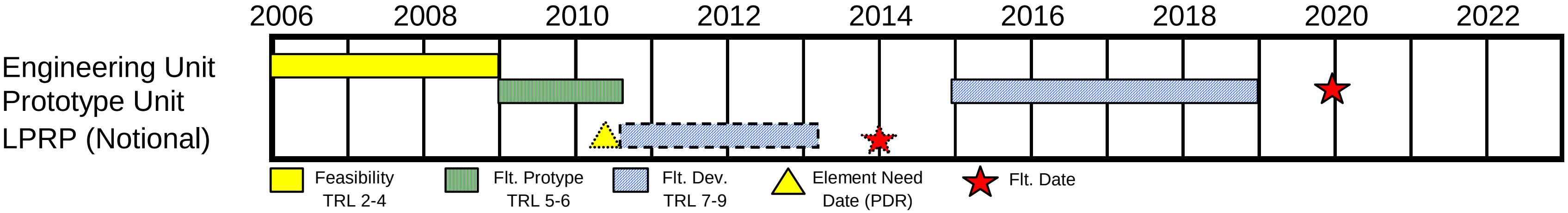
ISRU Development & Integration Strategy

- **Develop ISRU through phased ground development without requiring LPRP missions**
  - LPRP missions would reduce risk of resource, process, and environment uncertainties that ground facilities could not adequately replicate
  - Technology and System development tasks be directed at Outpost applications but will also anticipate (not preclude) possible LPRP scale applications
- **ISRU Technology and Systems developed in 4 Phases** (2-3 years each phase)
  - Phase I: Demonstrate Feasibility
  - Phase II: Evolve System w/ Improved Technologies
  - Phase III: Develop 1 or more systems to TRL 6 Before Start of Flight development
  - Phase IV: Flight Development for Outpost
- **Be prepared to participate in robotic precursor missions should opportunity arise**
  - Site characterization, resource mapping, and/or ISRU precursor
  - Outpost ‘dress rehearsal’ mission

Regolith Excavation & Oxygen Extraction from Regolith



ISRU Precursor Demonstration (O_2 Production and Resource/Site Characterization)



Integrated Capability and Analog Site Demonstrations

Utilize laboratory and analog site demonstrations to:

- Demonstrate needed capabilities and operations for Lunar Outpost and technology/system ‘customers’
- Demonstrate evolution and incremental growth in technologies and systems for Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness).
- Unite separate technology development efforts within NASA
- Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia

	2007						2008												2009											
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Site Preparation & Outpost Construction																														
COTS blade on Chariot rover @ JSC								◆																						
Inflatible habitat burial									⬟																					
Area clearing/berm building filed demonstration												◆																		
Reactor mockup burial																											▲			
Oxygen Extraction from Regolith																														
PILOT H_2 reduction reactor field test @ Desert RATS															▲															
- Includes: excavator & O_2 liquefaction & storage																														
ROxygen H_2 reduction field test @ Desert RATS															▲															
- Includes: excavator & high pressure O_2 storage																														
Integrated Carbothermal reduction reactor & Solar Concentrator															▲															
RESOLVE H_2 reduction field test																	▲													
Upgraded ROxygen reactor with Solar Concentrator																											▲			
Full-scale Carbothermal reduction reactor & Solar Concentrator																											▲			
Site Characterization & Resource Prospecting																														
K10s with GPR and 3D lidar at Haughton	◆																													
RESOLVE drill integration onto CMU rover at CMU			▲																											
K10s with GPR and Neutron Spectrometer at ARC					◆																									
RESOLVE drill/CMU rover field test at CMU						▲																								
Combined K10 and RESOLVE/CMU field test												▲					▲													

▲ = In-Situ Resource Utilization (ISRU)-led Demo

◆ = Human-Robotic Systems (HRS)-led Demo

⬟ = Structures & Mechanics-led Demo

ISRU System & Surface Operations Ground Demo Plan

2008 **2009** **In Planning** **2010**

Site Preparation & Outpost Deployment

Inflatable Shelter concept

Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation

Perform area clearing and with Chariot & ISRU Blade

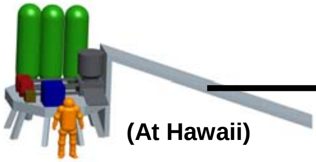
Add increased capabilities (ex. build berm and dig hole for reactor)

Examine other ISRU end-effectors on Chariot/Athlete

Examine ISRU end-effectors on other platform

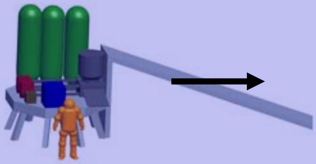
Add Autonomy & increased capabilities and durations to ISRU hardware.
Add new dedicated ISRU platform

Oxygen Extraction from Regolith



(At Hawaii)

Excavation and oxygen production from regolith with H_2 Reduction at 250 kg to 1000 kg per year rate for 1 to 5 days



Excavation and oxygen production from regolith using carbothermal reduction at 250 to 1000 kg per year with solar power

ISRU Precursor & Site/Resource Characterization

Integrate RESOLVE drill on CMU rover
(At CMU)

(At Hawaii-permafrost)

Integrate complete RESOLVE package on CMU rover

Add to Chariot

Add to Scarab

Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)